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(54) IMPROVEMENTS IN AND RELATING TO ROTATING ELECTRIC MACHINES

(71) We, MATSUSHITA ELECTRIC INDUSTRIAL COMPANY LIMITED, a Japanese company of 1006 Oaza Kadoma, Kadoma-shi, Osaka-fu, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed to be particularly described in and by the following statement:—

This invention relates to rotating electric machines.

In accordance with one aspect of the invention there is provided a rotating electric machine comprising a rotor having a permanent magnet with a plurality of poles there-around, a stator core made of magnetic material and having a plurality of salient poles there-around, and a plurality of stator coils one being wound on each of said salient poles and which are connected to each other so as to form a stator winding having a plurality of phases, the number of salient poles being a multiple of the number of phases and less than the number of permanent magnet poles.

Other features and advantages of the invention will appear from the following description of an embodiment thereof, given by way of example, and the accompanying drawings, in which:—

Figure 1 is a schematic view of a three-phase twenty-pole type DC motor having an arrangement of stator salient poles and rotor permanent magnet poles in accordance with one preferred embodiment of the invention;

Figure 2 shows a circuit diagram of an arrangement for producing a control signal to regulate the speed of a rotating electric machine such as that of Figure 1, and

Figure 3 is a graph indicating the waveform of the control signal obtained by the circuit of Figure 2 when used with the motor shown in Figure 1.

Before proceeding with the description of this example of an embodiment of the invention, it is to be observed that a multipole structure is indispensable for a rotating electric machine which is to operate at low speed. This type of machine presents difficulties in manufacture; the multipole permanent magnet of the rotor can be made without undue difficulty but the stator and its windings are complicated.

A conventional multipole stator has a magnetic member formed with a plurality of teeth, or pole members, and slots. As the number of poles increases, the slots become narrower in width, increasing the difficulty of winding the stator coils directly and rapidly on the pole members.

In lap winding also, the number of stator slots is a multiple of the number of poles of the rotor magnet. All slots are occupied by stator coils and many stator coils are required. The coils are usually pre-wound and are inserted into spaced slots so that the stator coils must necessarily be loose in the slots. Those portions of the stator coils which are in the slots contribute to the production of torque or electromotive force, but those portions of windings not within the slots do not contribute. These coil ends are relatively large in lap windings, since each coil extends over several slots. This increases copper losses, but iron losses are also increased, due to hysteresis and eddy currents due to the need to use narrow sections of magnetic material, with consequent high magnetic flux density.

In particular, however, vibration may occur due to the cogging force arising from the interaction between the stator core and the rotor magnet. The cogging force can be reduced by using a stator with skewed slots but such a stator is more difficult to wind.

The embodiment of the invention to be described affords a good compromise between

the conflicting requirements of performance and ease of manufacture.

Referring to Figure 1, there is shown the magnetic arrangement of a motor comprising a rotor yoke 10 carrying an annular permanent magnet 11 and a stator 12. The magnet is disposed around the inner periphery of the yoke, facing the stator, and is magnetised to present ten magnetic pole pairs, that is, twenty magnet poles. They are designated hereinafter as $N_{i(j)}$ and $S_{i(j)}$, where i=1, 2, 3, 4 or 5 and j=1 or 2; N means a north pole and S a south pole. The stator core 12 has fifteen salient poles x_i, y_i, and z_i where i=1, 2, 3, 4, 5. The top part of each salient pole, facing the rotor permanent magnet, is wider than the root portion, to accommodate the stator coil. This facilitates the winding of the stator and the stator offers a low reluctance for the magnetic flux from the rotor permanent magnet. On the lower part of the stator poles, stator coils X_i, Y_i and Z_i where i=1, 2, 3, 4 or 5 are wound. A stator winding consists of three stator phase windings X, Y and Z. As shown in Figure 1, the stator phase windings X, Y and Z include five stator coils pertaining to the same phase, X_i where i=1, 2, 3, 4 and 5; Y_i where i=1, 2, 3, 4 and 5, and Z_i where also i=1, 2, 3, 4 and 5. Each of the stator coil groups X_i, Y_i and Z_i is suitably connected to form a stator phase winding; the phase windings are spaced from each other by one hundred and twenty electrical degrees.

A cogging force will be generated by an interaction between the rotor permanent magnet and the core of the stator, made of magnetic material such as iron, even if the stator core is not energized by applied current. The permanent magnet of the rotor has a plurality of magnetic poles, each of which exerts an attractive force on the stator core. The nature of the force between the stator and the rotor is influenced by the shape of the stator core and the distribution of the magnetic charge in the rotor permanent magnet. Mathematically the cogging force is analysed by the convolution of the stator shape function defined by the shape of the stator core and the rotor magnetic distribution function related to the magnetic charge of the rotor permanent magnet. For example, in a rotating electric machine in which the stator core has sixty slots and the rotor permanent magnet has twenty poles, the stator shape function is represented by a periodic function with a fundamental period of sixty cycles per revolution, and the rotor magnetic distribution function is represented by a periodic function with a fundamental period of twenty cycles per revolution. Such a stator shape function expanded in Fourier series can be shown to have a fundamental component with a frequency of sixty cycles per revolution, and its harmonic components, and the rotor magnetic distribution function can be similarly shown to have a fundamental component with a period of twenty cycles per revolution, and its harmonic components. According to the properties of an orthogonal function, the convolution of the two functions is a linear combination of sine wave components which have frequencies which are common multiples of the frequencies of the components of the two functions. Hence, the cogging force is represented by a fundamental component with a frequency of sixty cycles per revolution and its harmonic components. The fundamental component of the cogging force is a sine wave with a frequency of sixty cycles. The amplitude of the fundamental component of the cogging force is related to the product of the amplitudes of the fundamental component of the stator shape function and the third harmonic component of the rotor magnetic distribution function. The number sixty corresponds to the fundamental period of the stator shape function, and the third harmonic component of the rotor magnetic distribution function, which has a frequency of sixty cycles, is inevitable because the intensity of magnetisation of a permanent magnet cannot be controlled precisely. The amplitude of the fundamental component in the cogging force, which is the sixty cycle sine wave, becomes large. As a result, an unduly large cogging force is generated sixty times per revolution of the rotor.

With a combination of a stator core with fifteen salient poles and a rotor permanent magnet with twenty poles, such as shown in Figure 1, the stator shape function consists of a fundamental component with a period of fifteen cycles per revolution and its harmonic components, and the rotor magnetic distribution function consists of a fundamental component with a period of twenty cycles per revolution and its harmonic components. The common multples of the frequencies of the components of the two functions are sixty and its multiples, and the fundamental component of the cogging force has a period corresponding to sixty cycles per revolution, but the amplitude of the fundamental component of the cogging force is the multiple of the amplitudes of the fourth harmonic component of the stator shape function and the third harmonic component of the rotor magnetic distribution function. The fundamental component of sixty cycles in the cogging force is not related to the fundamental component of fifteen cycles of the stator shape function. The fundamental cogging force is not due to the fundamental component of the stator shape function, since the number of the stator salient poles is less than that of the rotor permanent magnet poles. Consequently, such a rotating electric machine generates a smaller cogging force, and rotates more smoothly than prior art machines. Because it

can be made largely free from wow and flutter, it is especially suitable for use in audio equipment.

As the stator can be made with few stator salient poles, the spacing between adjacent poles can be made relatively wide; the number of the stator coils is also less, and the coils can be wound directly on each of the poles. If the width of the inner or lower part of the stator pole, on which the coil is wound, can be narrower than the outer or top part of the pole without magnetic saturation, the length of the coil ends which are portions of the stator coils not within the slots and which do not contribute to the revolving torque decrease, and this results in lower copper loss. Further, iron losses are also decreased, as the stator has a small number of poles so that each poles does ot have to be especially narrow.

The explanation of cogging force applies to the condition when the rotor magnetic distribution function does not include harmonic components of frequency less than twenty cycles per revolution. But, in practice, the rotor magnet has a variation of magnetisation around its poles. In this case the rotor magnetic distribution function may include a component with a frequency of one cycle per revolution, and its harmonics. As the stator shape function has a component of fifteen cycles per revolution, and its harmonics, the convolution of the stator shape function and the rotor magnetic distribution function may include components with three periods of fifteen cycles, thirty cycles and forty-five cycles per revolution. The component of fifteen cycles per revolution is due to the fundamental component of the stator shape function in the stator core having fifteen salient poles. The part of the stator pole which faces the rotor magnet can be wide, so long as the stator coil can be wound without difficulty. A wide top part of the stator pole decreases the amplitude of the fundamental component of the stator shape function and the cogging force component of fifteen cycles per revolution is reduced. The components of thirty and forty-five cycles per revolution are the higher harmonic components and are due to the harmonic components, higher than fifteen cycles per revolution, in the stator shape function.

Referring again to Figure 1, the reference numeral 13 indicates the centre, and 14 and 15 the edges of the periphery of the stator pole Z_5. The gap between each edge, 14 and 15, of each stator pole and the adjacent permanent magnet is made greater than at the centre 13. With this arrangement the amplitudes of the higher harmonic components in the stator shape function are reduced, and the cogging force is correspondingly reduced.

When current flows in a stator phase winding of Figure 1, the stator coils pertaining to that phase winding interact with the magnetic flux from that portion of the rotor magnet facing the stator coils. If there is a magnetic unbalance or non-uniformity in a plurality of the rotor magnet poles, the magnetic flux which is gathered in each of the stator coils has an unbalance corresponding to the unbalance among the rotor magnet poles, but the magnetic unbalance of the magnetic flux in the stator phase winding is reduced, due to the fact that the stator phase winding consists of five stator coils. The effect of the magnetic unbalance of the rotor magnet poles on the motor revolution is accordingly reduced. In Figure 1, the stator coils belonging to one stator phase winding are arranged at a uniform pitch around the periphery of the stator core; the total magnetic flux in one stator phase winding at a particular instant is the same as that after the rotor has rotated mechanically by 360°/5, i.e. or electrically $2\times360°$, if all the stator poles are considered magnetically equivalent and the number of turns of the stator coils is the same. In other words, the stator phase winding X including stator coils X_i acts with the rotor magnet poles $N_{i(1)}$, and after the rotor has rotated through 360°/5, the stator phase winding X again acts with the rotor magnet poles $N_{i(1)}$. The pitch of two magnetic pole pairs ($N_{i(1)}$, $S_{i(1)}$), or ($N_{i(2)}$, $S_{i(2)}$) of the rotor magnet corresponds to the angular pitch of the stator salient poles pertaining to the same stator phase, such as the angular pitch between X_i and X_{i+1}. While the rotor rotates mechanically through 360°/5, the stator phase winding is traversed by the two rotor permanent magnet pole pairs, that is, four magnetic poles; the stator phase winding alternately interacts with two pole pair groups only of the rotor permanent magnet, as the motor rotates. In the above, the rotor permanent magnet is described as having pole pairs ($N_{i(j)}$, $S_{i(j)}$) where $j=1$ and 2, for easy description, but it is to be noted that the complete rotor permanent magnet can be considered to be divided into two groups or 'states' and the stator phase windings interact alternately with members of these two groups only. The number of such groups of the rotor magnet will be referred to hereinafter as the number of 'states'. For example, in the example above, the motor has two states. The fluctuations of generated torque decrease as the number of states is decreased.

In Figure 2, a reference numeral is indicated diagrammatically at 16 for the motor shown in Figure 1. One terminal of each of the stator phase windings X, Y and Z is connected together to one power supply terminal 17. The other terminal of each stator phase windings X, Y and Z is connected to a point 18 through switching means 19, 20 and 21, respectively. Two resistors 22 and 23 of resistance r_1 and r_2 are connected in series

across the terminals 17 and 24 of the power supply, of polarity as indicated. A resistor 25, of resistance r_3, is connected between the point 18 and power supply terminal 24.

The switching means 19, 20 and 21 are arranged to operate selectively, in accordance with the position of the pole pairs of the rotor permanent magnet relative to the stator phase windings X, Y and Z, thereby to supply current to windings X, Y and Z in turn, causing the rotor to rotate. A counter electromotive force (CEMF) is thereupon induced in said stator winding. A potential difference e_1 is developed between the point 18 and the junction point 29 of resistors 22 and 23; this voltage will be proportional to the CEMF if the condition $(r_a/r_3)=(r_1/r_2)$ exists, where r_a is the resistance of each stator phase winding of the motor 16. Since the CEMF is proportional to the speed of the motor, the voltage e_1 can be used as a speed control signal.

The second terminals of the stator phase windings are also connected respectively to the anodes of diodes 30, 31 and 32, the cathodes of these diodes being connected together at point 33.

A voltage e_2 developed between the point 33 and point 34, which is the point of common connection of windings X, Y and Z, will be the CEMF after rectification by the diodes 30, 31 and 32. This voltage e_2 does not include any component due to the currents flowing in the stator windings through the switches 19, 20 and 21, since these currents are excluded from terminal 33 by the diodes. The voltage e_2 is therefore proportional to the motor speed, and it can also be used for controlling the motor.

Further, if a speed responsive means is provided, as in Figure 2, the signal it provides can be compared with a reference signal and the difference signal, after amplification, can be used to control the motor, to cause it to be run at a substantially constant speed.

The reference signal can be a D.C. signal: in which case the difference signal may include any ripple component present in the output signal from the speed detecting means. Such ripple component should be kept as small as possible.

Figure 3 shows the voltages e_1 and e_2; it will be seen that the voltages are induced alternately in only two states. If one of these signals is to be used for controlling rotor speed, the current supplied to the stator winding depends on the voltages e_1 or e_2 because the difference signal, after amplification, commands said current. The rotor will rotate uniformly if the number of states is small.

A group of adjacent stator salient poles associated with only one stator coil of the respective stator winding phases can be considered a stator element. In the case of the motor shown in Figure 1, a stator element will thus consist of three stator salient poles, facing two pole pairs of the rotor permanent magnet.

If a stator element faces p pole pairs of the rotor permanent magnet, the magnetic flux in each stator winding has p states. As the number of states has a direct bearing on wow and flutter, the number of states should be as low as possible. In a five phase rotating electric machine, the stator element will have five stator salient poles, and must face two pole pairs, that is, four poles, of the rotor magnet if two states are to be obtained. However this combination is not satisfactory, and is not in accordance with the invention, because the number of the stator poles is greater than the number of rotor poles. Accordingly, the stator element is arranged to face three pole pairs, that is, six poles, of the rotor; such a motor has three states. Generally, if the stator winding has (2n+1) phases where n is an integer, then it is adequate if the number of permanent magnet poles to the number of stator poles is in the ratio of $(2n+2)/(2n+1)$ and the number of states is (n+1). If the stator winding has (2n) phases, the ratio of permanent magnet poles to stator poles should be $(n+1)/n$ and the number of states is (n+1). A machine which has only two states must have rotor poles and stator poles in a ratio of 4/3 for three phase winding or 4/2 for two phase winding. A two phase machine is however non self starting when used as a DC motor, because the number of the rotor poles is an integral multiple of the number of stator poles, so that the three phase machine is to be preferred. When an electronic commutator is used, the less the number of phases, the less the number of electronic components in the driving circuits, so that the three phase machine is desirable for this reason also.

Various modifications may be made to the embodiments described. For instance, the stator winding can be energized by AC current and the machine can be operated as a multipole type synchronous motor running at a low synchronous speed.

WHAT WE CLAIM IS:—

1. A rotating electric machine comprising a rotor having a permanent magnet with a plurality of poles therearound, a stator core made of magnetic material and having a plurality of salient poles there-around, and a plurality of stator coils one being wound on each of said salient poles and which are connected to each other so as to form a stator winding having a plurality of phases, the number of salient poles being a multiple of the number of phases and less than the number of permanent magnet poles.

2. A rotating electric machine in accordance with claim 1, wherein said stator has (2n+1) phases, and the ratio of the number

of poles of the rotor to that of the stator poles is $(2n+2)/(2n+1)$.

3. A rotating electric machine in accordance with claim 1, wherein said stator has 2n phases, and the ratio of the number of rotor poles to that of stator poles is $(n+1)/n$.

4. A rotating electric machine in accordance with claim 2, wherein the stator winding has 3 phases, and the ratio of the number of rotor poles to the number of stator poles is 4/3.

5. A rotating electric machine in accordance with any of the preceding claims, wherein the radial gap between each stator pole and the rotor poles varies at different angular positions.

6. A rotating electric machine in accordance with claim 5 wherein said gap is smaller at the centre of the stator pole than at both edges of said pole.

7. An electronic commutator D.C. motor comprising a rotor having a permanent magnet presenting p poles; a stator core having q salient poles, the ratio of p to q being 4/3; q stator coils, each of which is wound on a respective one of said salient poles, said coils being connected to form a stator three phase winding; speed responsive means responsive to the speed of said rotor; reference signal means and comparison means for comparing a signal from said responsive means with a reference signal; and means controlled by the output of said comparison means for controlling the energisation of said motor.

8. An electronic commutator D.C. motor in accordance with claim 7, wherein said speed responsive means includes means for deriving a voltage which is the counter-e.m.f. developed by rotation of said rotor, and said voltage is applied to said comparison means.

9. A rotating electric machine substantially as described with reference to the accompanying drawing.

10. A rotating electric machine and electric control means therefor substantially as described with reference to the accompanying drawing.

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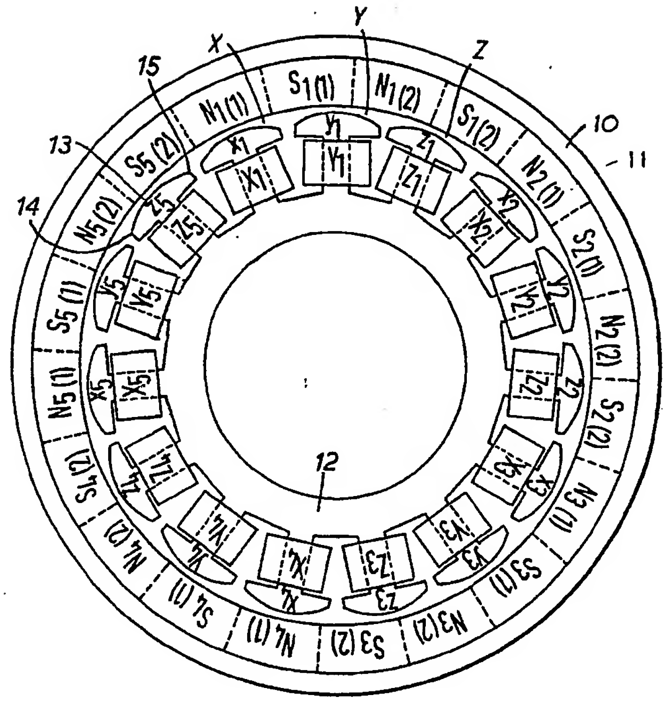
X
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FIG.1.

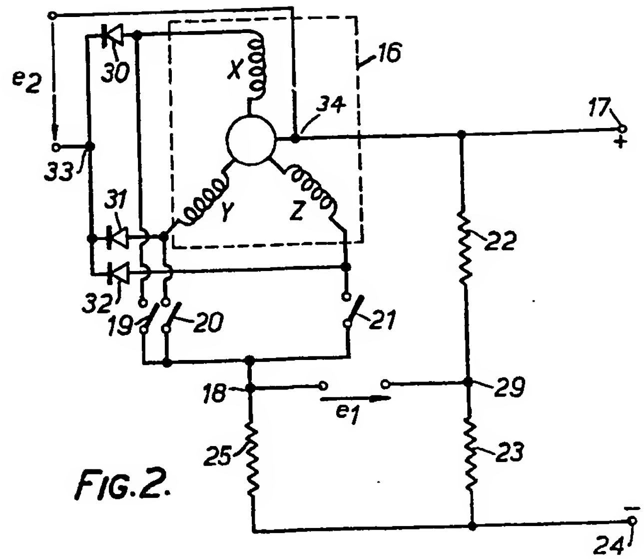

FIG.2.

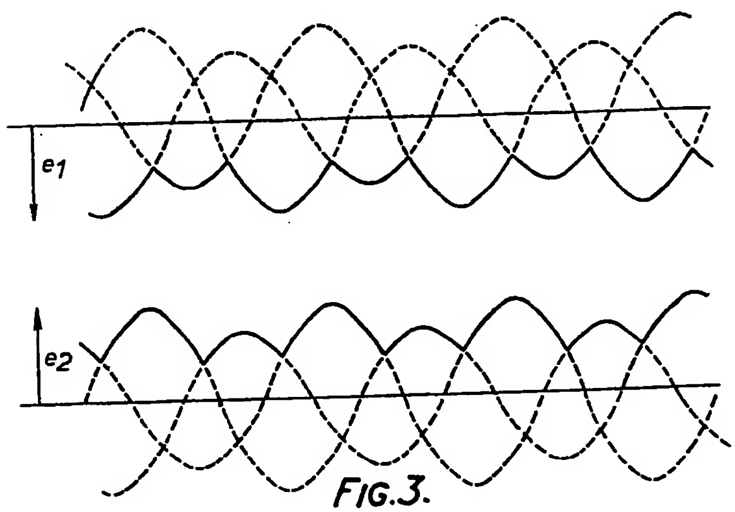

FIG.3.